Experimental Simulation of a Multiple Beam Optical Waveguide

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Two mirrors, 15 centimeters in diameter and 25 meters apart, form an optical delay line which can store two gaussian beams for 342 round trips or 60 microseconds. This paper reports experiments which studied the intensity profiles, the phase fronts, and the cross scattering between these beams after their retrieval from the delay line. In certain respects, the delay line simulates a multiple beam guide made of 684 mirror periscopes. The experimental results permit an estimate of the beam capacity, the crosstalk, and the transmission length of such a guide.

I. INTRODUCTION

The possibility of sending a multitude of gaussian light beams down a single lens waveguide has recently been suggested as an inexpensive means of multiplying the capacity of the waveguide.[1,2] Though the beams would overlap along the guide, appropriate optics could separate them in the receiver.

The density of resolvable beams in the system is determined by beam distortion and scattering rather than the spread of the ideal beams. Smooth imperfections of the optical surfaces cause the beam to deviate from the exact position and distort its profile and cross section.[3] This limits the density of the beams and determines the receiver size required to secure reception. Surface irregularities that are small compared with the beam size result in scattering that is collected by receivers of adjacent channels.[4] This crosstalk increases with the receiver size, the density of beams, and the number of scattering elements. The purpose of this experiment was to check the amount of distortion, to determine the receiver size required, and then to measure the scattering and find out what beam density and transmission dis-

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tance could be achieved with tolerable crosstalk. In a multiple beam guide, front surface mirrors probably will be preferred to lenses because, for the large apertures needed, lenses are apt to have imperfections within the material. A first simulation of such a mirror guide was tried here by folding two beams into a two-mirror cavity with a size comparable to one guide section. The setup was similar to optical delay lines built previously,[5] except that this line was optimized to exploit its full capacity.[1]

In a delay line, the folded beam wanders about the mirror surfaces, being submitted to always new and statistically independent mirror imperfections, similar to the waveguide situation. The distortion is therefore equivalent to the distortion in a guide. Two beams launched simultaneously follow adjacent paths comparable to two adjacent beams in a multiple beam waveguide. Their cross-scattering is equivalent to the cross-scattering of two neighboring beams in a waveguide.

II. THE FOLDED-BEAM CAVITY

Figure 1 shows the experimental setup with the two cavity mirrors in the background. Disregard the beam splitter for the moment and assume that only one gaussian beam, beam 1, is injected at an angle through the center hole in the front mirror. By introducing astigmatism to this mirror, as indicated by the arrows, the beam can be kept in the cavity for many round trips, writing a Lissajous pattern on each mirror.[5] Careful adjustment of this pattern permits recovery of the beam through the same hole at a slightly different angle. Figure 1 shows the two-lens telescope used to inject the laser beam and a little mirror at the focus of the telescope which deflects the output beam, beam 4, into a photomultiplier.

The delay line was designed so that a maximum number of round trips could be accommodated in an available 6-inch conduit, 25 meters long, with the beam axis never approaching the wall and the center hole closer than 2.5 beam radii. This clearance ratio is identical to the density factor k defined in Ref. 1.

Also from Ref. 1 one obtains the possible number of round trips

$$N_{\text{cavity}} = \frac{A^4}{4d^2\lambda^2k^4} \tag{1}$$

in a delay line of radius A and length d, using an optical wavelength λ. To allow for a slight misalignment of the conduit sections, we assumed an unobstructed cross section 12 cm in diameter. For $A = 6$ cm, $d =$

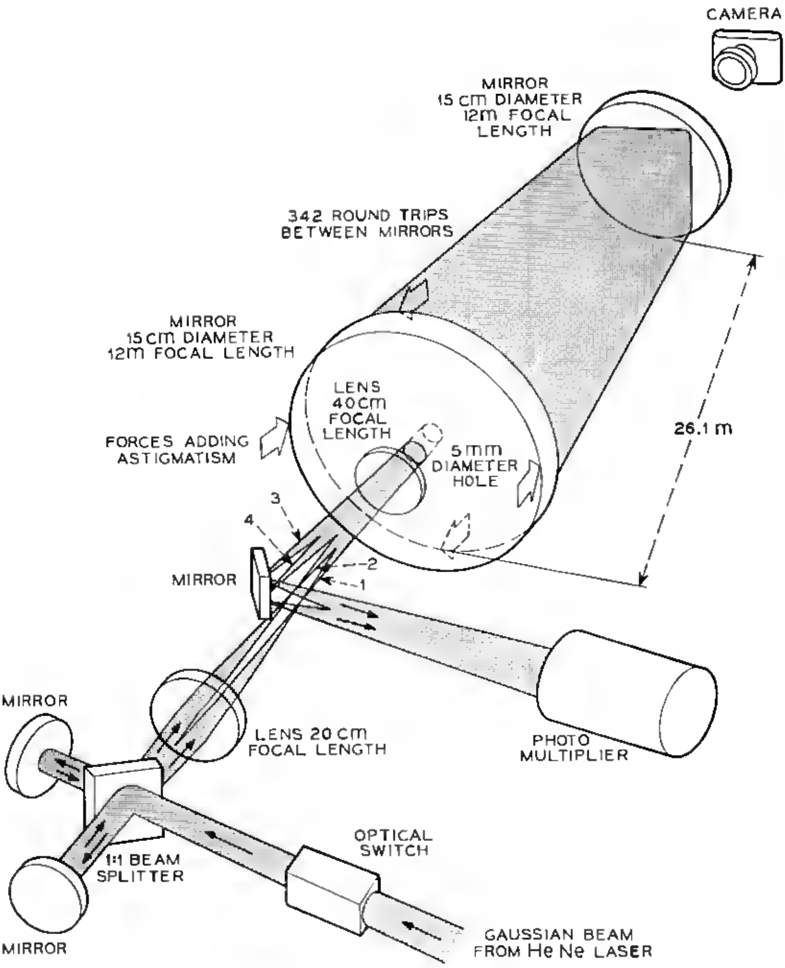

Fig. 1 — Injection and recovery of the two beams after 342 round trips in the delay line.

25 m, and $k = 2.5$, one obtains $N = 335$. We chose $342 = 18 \times 19$ round trips because, for optimum conditions, N must be a multiple of two consecutive integers.[1,5]

For this optimum design, Ref. 1 demands a focal length

$$f = \frac{d}{2 + \pi/N^{\frac{1}{2}}} \tag{2}$$

for the undistorted mirror and focal lengths

$$f_{h,v} = \frac{d}{2 + \frac{\pi}{N^{\frac{1}{2}}} \pm \frac{\pi}{N}} \tag{3}$$

for the astigmatic mirror in the horizontal and vertical planes, respectively. We chose $f = 12$ m and adjusted the mirror spacing to 26.1 m. This spacing was critical to within 1 mm. The astigmatic mirror had focal lengths $f_{h,v} = 12$ m $\pm$ 5 cm corresponding to a surface deflection of ± 1 micron at the mirror edge when forces were applied as shown in Fig. 1. Both mirrors were 2.5 cm thick, 15 cm in diameter, polished spherical within $\lambda/10$, and coated for high reflectivity at 6328 Å, the wavelength of the He-Ne laser used.

The optimum design requires a beam radius

$$v = \frac{(d\lambda)^{\frac{1}{2}}}{N^{\frac{1}{4}}} \tag{4}$$

at the input.[1] For the chosen parameters $v = 1$ mm. We provided a center hole with a radius $kv = 2.5$ mm in the front mirror. The radius v is also the minimum radius the beam ever has in the cavity. Figure 2 is a photograph taken at the back of the rear mirror. It shows that

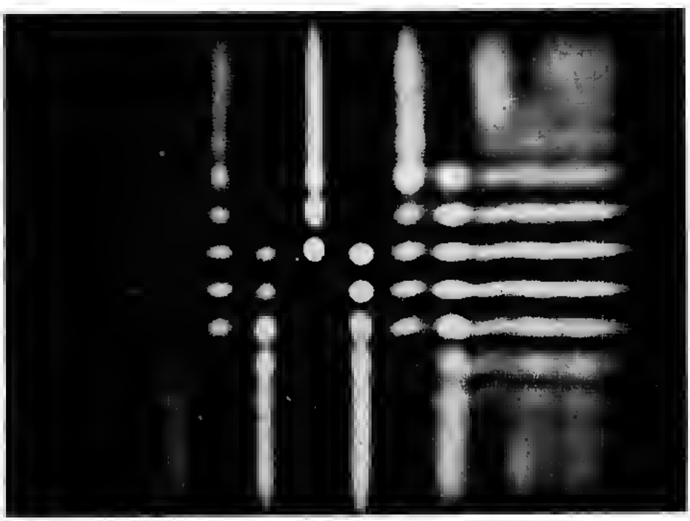

Fig. 2 — Lissajous pattern of one beam photographed at the back of the rear mirror.

the beam size is smallest in the center of the pattern. The beam widens horizontally when it is displaced horizontally and widens vertically when it deviates vertically. Consequently, the beams have elliptical cross sections everywhere except along the pattern diagonals. The ratio of the maximum to the minimum beam radius is

$$\frac{u}{v} = \frac{N^{\frac{1}{2}}}{\pi} \tag{5}$$

for the optimum design; consequently $u = 5.9$ mm.

To recover the beam after 342 round trips without interference from other paths, the Lissajous patterns on the mirrors must form 18 lines and 19 rows of spots as shown in Fig. 2. The spacing of these lines and rows decreases toward the pattern edges; the spots overlap as their sizes increase. In the middle of the pattern, the spots are spaced center-to-center 6 mm horizontally and 5 mm vertically. The same spacing holds for the spots around the center hole of the front mirror. A better output beam was obtained from the rectangular arrangement shown in Fig. 2 than from one with equal horizontal and vertical spacing. A possible cause of this is discussed in the Section III.

Figure 2 shows an increase in the pattern brightness from right to left caused by the nonuniform mirror transmission, which does not reflect a variation in beam intensity. The total loss for 342 round trips was 4.0 dB or 0.135 per cent per reflection. This loss is about three times that of the best mirrors reported.[6] Unfortunately, the reflection maximum of the rear mirror was not exactly centered on the 6328 Å laser line, and the coating was not completely uniform across the surface.

The conduit was mounted along the laboratory wall between two concrete tables which supported the ends. The mirrors were inside the airtight conduit. Their position and the astigmatism were adjusted from outside. Without evacuation, convection inside the pipe caused the beam to drift off the exit hole within minutes. A 1-inch fiberglass insulation around the pipe did not improve this situation. After the pipe had been evacuated to a pressure of 3 torr, the proper alignment could be kept for hours.

III. BEAM DISTORTION MEASUREMENTS

In a well-aligned perfect cavity, the input and output beams pass the center hole with the same size and phase front, but with a slight difference in propagation angle. This permits their separation at the

focus of the launching telescope. Figure 3 shows a vertical and a horizontal scan of the output beam. The scans deviate little from the expected gaussian profiles. The width agrees well with that of the input beam. Obviously the high quality mirrors do not introduce appreciable distortion even after 684 reflections. This agrees with previous observations.[3]

The mirror imperfections might be large enough, however, to make the beam stray from its predicted path. The output beam did not show this deviation, as we could and did correct for it by adjusting the mirrors. But there was some evidence that this effect is not completely negligible. Theory predicts that, with perfect alignment, changing the direction of the input beam only changes the direction

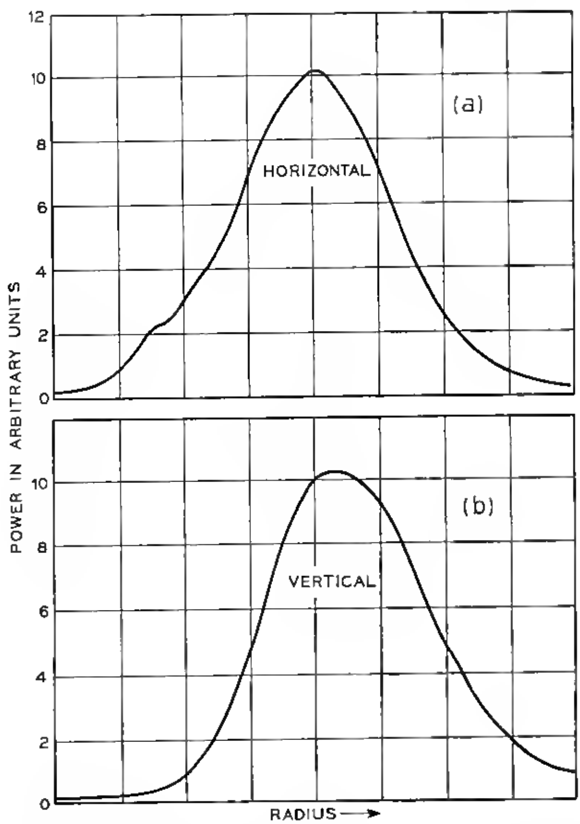

Fig. 3 — Horizontal and vertical scan of the beam after 684 reflections.

of the output beam, but both beams stay centered in the hole. Of course, this operation simultaneously changes the pattern size and either brings the outer paths close to tbe wall, or the inner paths close to the hole. Before we noticed any interference at the wall or the hole, the output beam would start moving off the hole center when we changed the input beam direction. Comparable experiments with and without astigmatism in a system with fewer round trips suggests that this imperfection is associated mainly with the way the astigmatism is introduced.

Straying from the designed beam path will cause crosstalk in a multiple beam guide. To learn more about this effect, the input was split into a lower beam (1) and an upper beam (2), as shown in Fig. 1. Beam 2 writes a pattern which is the mirror image of Fig. 2 about the horizontal axis. Figure 4 shows the composite pattern written by both beams. Tbe output beams 3 and 4 are separated one above the other at the focus of the telescope and can be recovered separately or together by moving the deflection mirror up or down. Tbe profile of beam 3 is very similar to the one shown in Fig. 3. Figure 5 shows tbe interference pattern of the output beams displayed on a card in front of the receiver. The straight lines indicate that the phase fronts of the two beams are tilted with respect to each other but are not noticeably different otherwise.

To avoid too optimistic a conclusion from this result, one has to investigate the respective paths of the two beams. To every reflection made by one beam, one can find a reflection by the other which occurs not more than 6 mm away. The effects of small imperfections add up in a commutative way. Consequently, the sequence of reflections is immaterial, and the total distortion of one beam is closely related to the distortion of the other beam because of their neighborhood in the cavity. The nature of this neighborhood is the same as with two beams in a multiple beam transmission system when they are launched and received 6 mm apart.

IV. BEAM SCATTERING MEASUREMENTS

A better analysis of the light output from the cavity is possible when light pulses are injected. This was done by pulsing the laser output at a rate of 1 kHz for intervals of 100 ns using a polarization switch as shown in the foreground of Fig. 1.[7] The pulses were shorter than the cavity round trip time of 174 ns so that the output from successive round trips could be resolved. The total delay of the primary

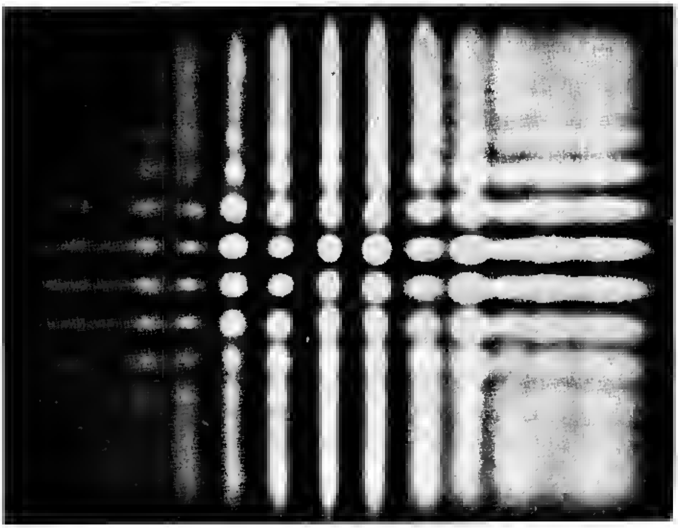

Fig. 4 — Composite pattern of both beams at the back of the rear mirror.

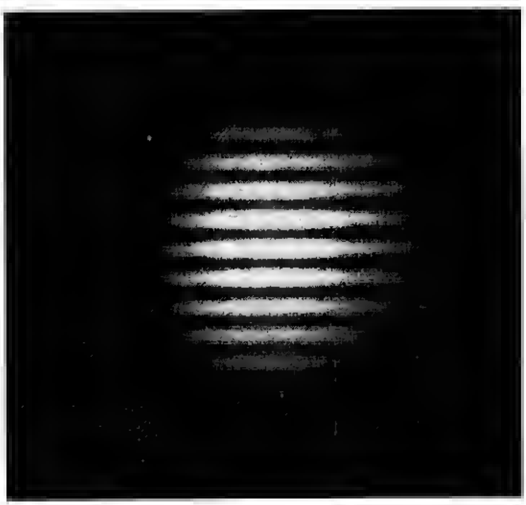

Fig. 5 — Interference pattern of the two beams after 684 reflections.

output pulse was 59.5 μs, confirming the projected number of 342 round trips.

Much weaker pulses were detected before and after the primary output pulse at periodic intervals corresponding to 18 or 19 round trips. By alternately blocking beams 1 and 2, we could attribute some of these pulses to beam 1 and some to beam 2. Blocking beam 2 avoids the strong primary pulse in beam 3 so that the weak pulses can be amplified without saturating the photomultiplier.

Figure 6 shows pulses generated by beam 1 which leave the cavity along path 2. They were detected by moving the deflection mirror into this path. The numbers indicate the round trips completed before detection. Pulse 342 was caused by the primary output pulse which leaves the cavity along beam 4. Although it is not intercepted by the deflection mirror, some scattering outside the cavity resulted in a weak light pulse in the receiver. The other pulses can be attributed to scattering inside the cavity. Investigation of the Lissajous pattern shows that the beam path tends to approach the center hole whenever 18 to 19 round trips are completed. The occurrence of scattered pulses with this periodicity suggests that the beams close to the center hole are responsible for the scattering.

Figure 7 is a sketch of the area around the center hole as viewed from the back of the front mirror. The numbers indicate the round trips completed before the respective reflection. The arrows show

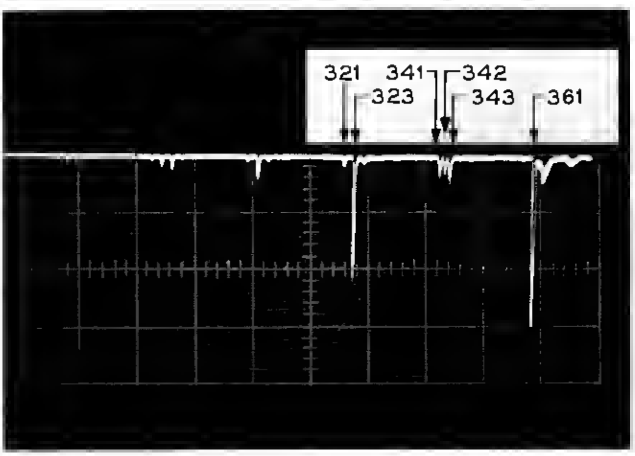

Fig. 6 — Pulse train of scattered light received in beam path 2 when only beam 1 is injected. The numbers indicate the round trips completed before reception.

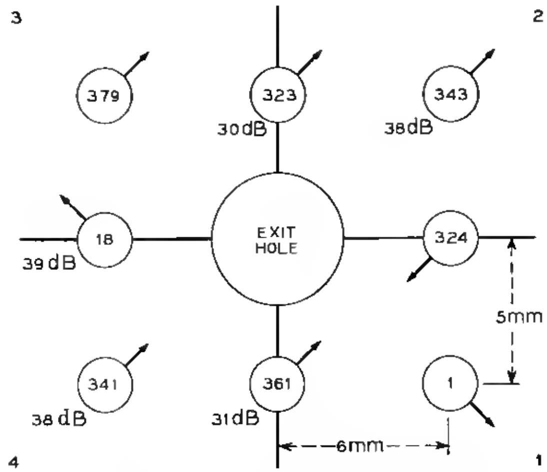

Fig. 7 — The reflections around the exit hole as seen at the back of the front mirror. The numbers indicate the round trips. The arrows point to the quadrant where the scattering is picked up. The dB values represent the ratio of total output to scattered light.

in which direction a particular beam scatters, that is, in what beam path it will be picked up. For example, all dots pointing toward quadrant 2 were received in beam path 2 and are present in the pulse train of Fig. 6. The additional pulses not labeled in Fig. 6 originated from reflections farther away from the hole. They were omitted in Fig. 7 to avoid confusion. The signal in Fig. 6 was calibrated by comparing it with the signal from the primary output pulse reduced by a 40-dB standard attenuator. The dB values in Fig. 7 represent the signal-to-crosstalk ratio obtained by calibrated reception in beam paths 2 and 3.

These observations seem to support the theory that every reflection scatters a small amount of light into a narrow cone about the primary beam.[4] Refocused by the mirrors, this light stays close to the beam; contributions from successive reflections add in power. This is why, after 323 round trips, 9 dB more scattering was measured than after 18 trips, though at that time both beams are the same distance from the hole. Notice that the dB levels indicated in Fig. 7 are related to the power of the output beam. If we consider the attenuation and relate the scattering levels to the beam powers at the respective reflections, the scattering is 42.8 dB below that power after 18 round

trips and 39.2 dB after 323 round trips. The difference is 12.6 dB, that is, the scattering has increased 18 times from the 18th to the 323rd round trip, or about proportionally to the number of round trips. If the scattering could be measured after one reflection, the scattered power should be 30 dB + 10 log 646 = 57 dB smaller than the total power of the primary beam.

This, of course, holds only for the specific arrangement shown in Fig. 7: an output hole 5 mm in diameter and a beam being displaced by about 5 mm from this hole. If tbe reflection occurs 1.56 times farther away from the hole (for example, reflection 341 or 343), the scattered power intercepted by the hole is about 8 dB smaller. From this it is concluded that the scattered power density decreases with about the fourth power of the distance from the hole.

This result is subject to the specific measuring arrangement used, in particular the directional properties of the receiver. In our case, because of the deflecting mirror, the receiver collected one-quarter of the cone of light falling through the exit hole. The observation of a rapid fall-off of the scattered light around the primary beam agrees with measurements reported in Ref. 4. The fact that scattered signals occur even after the primary beam has left the cavity means that the cone of scattered light, though intercepted partly by the exit hole, keeps travelling around in the cavity.

V. AN EQUIVALENT MULTIPLE BEAM GUIDE

Envisage the two cavity mirrors to be replaced by a sequence of thin lenses with the same focal length and spacing. Consider the beam to be unfolded along this path. Periscopic mirror arrangements could be used as well as lenses.[8] Each periscope consists of two mirrors, thus there are two reflections at every focuser, twice as many as in the delay line. Consequently, after traveling through 684 sections, 25 m in length, the beam suffers a loss of 8 dB or about 0.47 dB per km.

In contrast with the delay line, it is not necessary to introduce astigmatism in the multiple beam guide. If the guide is installed above ground, the pressure in the conduit will have to be reduced to a few torr, but evacuation seems unnecessary in an underground installation.[8]

The experiment demonstrated that two adjacent beams show negligible distortion and are fully separated after 684 sections, or 17 km. A receiver area of 5 mm diameter, the size of the exit hole, is sufficient

to collect practically all of the beam energy. It might be advantageous to reduce the detector diameter to 3 mm. Such a detector would still collect 90 to 95 per cent of tbe signal light but less of the light scattered from adjacent beams.

A double mirror periscope will cause twice the scattering of one delay line mirror. A detector witb the size of the exit hole at the end of a 648-section guide will consequently receive twice the scattering measured in the experiment, that is, a level of $30 - 3 = 27$ dB for two beams 5 mm apart and $38 - 3 = 35$ dB for two beams about 8 mm apart. The contributions from beams farther away decrease fairly rapidly. If one assumes a decrease with the fourth power of the spacing, one obtains a crosstalk level of about 27 dB for a beam surrounded by equal beams with a mutual spacing of 8 mm or 4 beam widths. Reducing the detector diameter to 3 mm should improve this level to about 31.5 dB.

The level that can be tolerated depends on various aspects of the complete transmission system, but for a comparative figure, regard the composite scattering from all beams as gaussian background noise. Then, with binary envelope detection and no other noise present, a crosstalk level of 20 dB would guarantee an error rate of 10^{-9}.

With this figure in mind, one might consider increasing the transmission distance to 4,000 sections, or about 100 km, allowing a total attenuation of 48 dB. This increases the crosstalk by about 8 dB resulting in a signal to crosstalk ratio of $31.5 - 8 = 23.5$ dB for a mutual beam spacing of 4 beam widths and a detector diameter of 1.5 beam widths. Reference 2 calculates a diffraction crosstalk of about 60 dB for this beam spacing which is completely negligible compared with the scattering effect.

The number of beams that could be transmitted with a mutual spacing of $k = 4$ beam widths in a guide equivalent to the investigated cavity is[1]

$$N_{\text{guide}} = \frac{\pi^4}{32} \frac{A^4}{d^2 \lambda^2 k^4}. \tag{6}$$

For a section length $d = 25$ m, a useful cross section of $A = 6$ cm radius, and $\lambda = 6328$ Å, one obtains about 600 beams. Filling the guide with this capacity, however, requires tbat the receivers have a better directional selectivity than the one used in the experiment. On the other hand, better selectivity would reduce the scattering received from other beams below what was measured.

VI. CONCLUSIONS

A He-Ne laser beam was injected into an evacuated 25-m delay line and extracted with negligible distortion and only 4 dB loss after 342 round trips. This corresponds to 60 μs delay. The absolute deviation from the ideal path could not be measured, but two beams injected simultaneously were found to be well resolved after 342 round trips.

The light scattered at every reflection from tbe main beam traveled in a narrow cone about this beam. The power density of the scattered light seemed to decrease with about the fourth power of the distance from the beam. The crosstalk caused by scattering from earlier round trips was 30 dB below the signal level.

A multiple beam waveguide equivalent to this delay line would have mirror periscopes spaced 25 m apart. It could transmit 600 beams over a distance of 100 km with an attenuation of 48 dB and a crosstalk level of 23.5 dB.

VII. ACKNOWLEDGMENTS

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REFERENCES

1. Gloge, D. and Weiner, D., "The Capacity of Multiple Beam Waveguides and Optical Delay Lines," B.S.T.J., *47*, No. 10 (December 1968), pp. 2095–2109.
2. Goubau, G. and Schwering, F. K., "Diffractional Crosstalk in Beam Waveguides for Multibeam Transmission," Proc. IEEE *56*, No. 9 (September 1968), pp. 1632–1634.
3. Gloge, D. and Steier, W. H., "Pulse Shuttling in a Half-Mile Optical Lens Guide," B.S.T.J. *47*, No. 5 (May-June 1968), pp. 767–782.
4. Gloge, D., Chinnock, E. L., and Earl, H. E., "Scattering from Dielectric Mirrors," B.S.T.J., *48*, No. 3 (March 1969), pp. 511–526.
5. Herriott, D. H. and Schulte, H. T., "Folded Optical Delay Lines," Appl. Opt. *4*, (August 1965), pp. 883–889.
6. Gronros, W., and others, unpublished work.
7. Steier, W. H., "Coupling of High Peak Power Pulses from He-Ne Lasers," Proc. IEEE, *54*, No. 11 (November 1966), pp. 1604–1606.
8. Gloge, D., "Experiments with an Underground Lens Waveguide," B.S.T.J., *46*, No. 4 (April 1967), pp. 721–735.